Lithium Target & Stripper Film Studies: FWP 56401 at ANL

Goals for FY2004 from the original proposal

Task 1: Prototyping of windowless liquid lithium targets

- Finish testing the 1-cm windowless target at a high-power electron-beam facility. ***This task was completed, see discussion below.***
- In addition to the nominal test conditions above, vary the e-beam current, lithium flow rate, etc. ***This task was also completed.***

Task 2: Development of thin-film liquid lithium strippers

- Continue tests with water jets to determine pressure/flow requirements for both the thick and thin films (requires the development of thickness and uniformity diagnostics for the water films). ***This task was completed as described below except that the diagnostics development was deferred to 2005.***
- Finish design of lithium pumps to match the pressure/flow requirements for both the thick and thin films. ***Drawings for a high pressure/low volume flow rate pump were completed, but the final parameter choices will be made following the tests with the pressurized chamber described below.***
- Construct the lithium pump required for the thin film application. ***This task was deferred due to reduced funding.***
- Construct the prototype thin-film lithium loop. ***The design of a pressurized system was completed and procurements and fabrication initiated during FY2004. Completion of this test chamber will be deferred until FY2005 funding.***

Task 3: Liquid metal working fluids for targets and strippers

- Complete and document the study of alternative liquid metal working fluids for targets and strippers in RIA. ***This task was deferred due to reduced funding.***

Progress in FY2004

Task 1: Prototyping of windowless liquid lithium targets

Experiments were conducted to demonstrate the stable operation of the windowless liquid lithium target under extreme thermal loads, equivalent to a 200 kW, 400 MeV/u uranium beam in RIA. The cross section of the windowless liquid lithium target was 5 mm $\times$ 10 mm and the velocity of the liquid lithium was varied up to 3.6 m/s. Thermal loads up to 20 kW within a beam spot of 1mm in diameter on the windowless liquid lithium target were applied by 1 MeV electron beams. It was demonstrated that the windowless liquid lithium target flowing at as low as 1.8 m/s stably operates under the beam powers up to 20 kW without disruption or excessive vaporization. The experimental setup included a lithium loop, beam line, and an electron beam source and various instrumentation. The behavior of the liquid lithium jet was visually observed to confirm a stable jet during heating. The temperatures and the background pressure were also monitored to evaluate the capability of the jet to handle an extreme thermal load without excessive vaporization. One mechanically movable, transverse thermocouple was mounted near the jet to measure the temperature distribution across the jet.

Task 2: Development of thin-film liquid lithium strippers

Producing a very thin, stable film jet with a high flow rate in a vacuum environment is a key element for this task. However, it is known that a liquid jet emanating from a nozzle is inherently unstable. This means that a slight disturbance in the jet is spontaneously amplified and the jet eventually breaks up into small droplets. The mechanism of droplet formation is capillary pinching due to surface tension of the liquid. An example of a typical stability diagram developed using linear stability theory is presented in Fig. 1. This figure conceptually maps the regions of instability using two dimensionless parameters; the Reynolds number, *Re*, and the Weber number, *We*, which are ratios of the inertia forces to the surface tension forces and of the inertia forces to the viscous forces, respectively. The Weber number and the Reynolds number are expressed as,

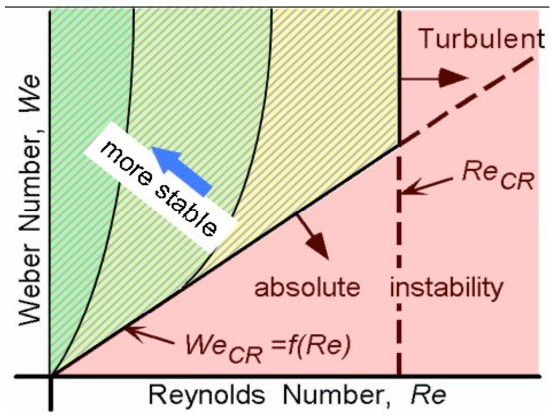

Figure 1. Schematic Representation of Stability Diagram for the Jet in Vacuum.

$$We = \frac{\rho U^2 R_h}{\sigma}, \text{ and } Re = \frac{\rho U R_h}{\mu},$$

where ρ is the liquid density, U is the average jet velocity, R_h is the hydraulic radius of the nozzle, σ is the surface tension of the liquid, and μ is the liquid dynamic viscosity. Two different modes of instability are possible: a) absolute instability, and b) convective instability. Absolute instability occurs when the surface tension forces of the fluid dominate over the inertia forces, i.e., the liquid does not even form a stable jet, but instead forms droplets as soon as it exits from the nozzle. As jet velocity is increased, fluid inertia becomes dominant and the instability mode shifts to convective, in which a disturbance propagates and grows only in the downstream direction. As the liquid exits from the nozzle, a continuous jet is formed that extends downstream to some breakup point. The yellow-green shaded areas in Fig. 1, where $We > We_{CR}$, represent the regions of convective instability where, the jet may be stable for some distance between the nozzle exit and the breakup point. Thus, conducting experiments to assess the feasibility of the liquid stripper is necessary only in this shaded area. In addition, because this figure uses only *Re* and *We*, a stability diagram is not expected to be an explicit function of any liquid properties, implying that the diagram should be universal and applicable to any liquid. This fact allows the use of Li simulants for establishing the region of stability instead of using Li, significantly reducing complexity, difficulty, and cost of performing experiments. These simulant results are then used to design a proof of principle thin film stripper system, which will successfully use liquid Li under hard vacuum conditions.

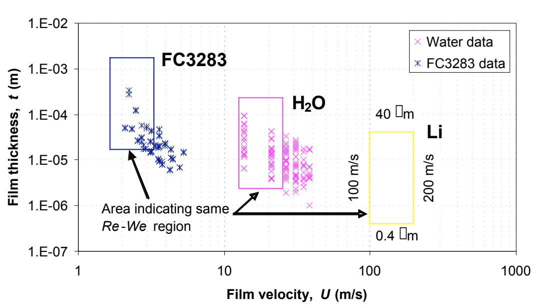

Figure 2. Film velocity and thickness to obtain identical Re and We for various working fluid.

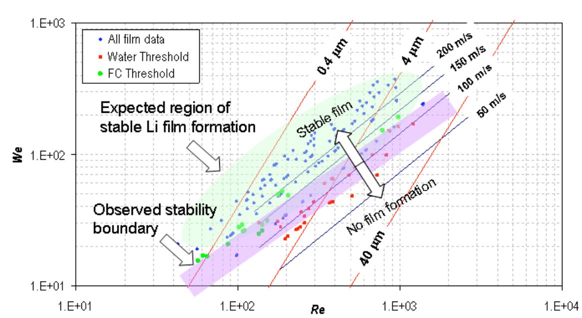

Figure 3. Stability Diagram and Li Film Velocity and Thickness.

After analyzing various potential Li simulants, water and 3M's FC-3283 were selected not only because of their inert and non-hazardous characteristics, but also, as shown in Fig. 2, the difference between physical properties of FC-3283 and those of water for the same combination of Re and We is similar to that between water and lithium. Therefore, comparing the results obtained for FC-3283 and water is expected to allow direct extrapolation of these thin film stability experimental results to lithium.

Our main results under Task 2 are the experimental data plotted in terms of *We* and *Re* numbers for FC 3283 and water, shown in Figure 3, and represent a film stability diagram. Blue dots shown in this figure indicate film formation for both water and FC-3283. Red and green dots show threshold data, i.e., the point at which a stable film is first observed for a given nozzle size and angle of incident. Good agreement between the results for FC-3283 and water strongly suggests that the stability diagram represented as a function of *Re* and *We* numbers is applicable to other fluids, including Li. The purple narrow zone indicates the boundary for the absolute instability and the green shaded area indicates the region where stable film formation is experimentally confirmed. Solid lines shown in this figure indicate projected lines of constant velocity (varying film thickness) and constant film thickness (varying the velocity) for lithium. This figure provides confidence that the formation of a thin liquid Li film of 4 μm at velocity > 100 m/s is highly likely.

Companion research carried out with ANL LDRD funding determined the type of stripper foils required for the RIA driver linac. An experiment with an 11 MeV/u uranium beam was carried out at Texas A&M University to determine the requirements of the first stripper foil. An experiment with an 85 MeV/u uranium beam was carried out at GSI to determine those of the second foil. The data from these experiments were analyzed and reported by the Colorado School of Mines group. The results indicate that the optimal foil for the first stripper could be lithium or beryllium with a thickness of approximately 300 micrograms/cm^2, corresponding to ~6 microns of liquid lithium. A demonstration of the feasibility of generating such a film of liquid lithium is the main goal of this project. The GSI experiment indicated that the optimal atomic number for the second foil is six (carbon) or somewhat more, with a thickness of 15-20 milligrams/cm^2. Hence, the demonstration of a film optimized for the second stripper is outside the scope of this project. It could be, for example, a rotating wheel of carbon or diamond.

Our second main Task 2 result is the lithium system currently being fabricated as both a proof of principle test, and for developing a thin film stripper for the RIA program. The design parameters for the Li thin film stripper system were determined based on the results of the hydrodynamic stability experiments described above. Preliminary calculations for an effective stripper that will not be thermally disrupted by the expected power in the RIA beam, indicates a target film thickness of 5 μm and a velocity of at least 50 m/s. However, the above results indicate that achieving a stable lithium film will require a jet velocity of 140 m/s and a 5 μm film thickness. This velocity will require a nozzle pressure of nearly 2000 psig. Thus, the maximum operating pressure of the system is set at 2000 psi, to assure adequate Li jet velocity. To provide for a broad range of nozzle driver pressures, this stripper demonstration system will be gas pressure driven. To allow time for meaningful observations, a lithium reservoir of approximately 20 liters has been chosen. The nozzle resides in the target chamber, which is under hard vacuum to simulate the RIA beam line. The lithium will be filtered before entering a commercial high-pressure nozzle. The lithium jet exiting the nozzle will be directed to impinge upon a sharp edged metal target, causing the jet to be deflected and broadened. Experiments will be run as a function of supply pressure, nozzle size (velocity) and nozzle composition, as well as jet impact location from the target edge and jet angle on the target.

A stainless steel containment room was erected to conform to the safety considerations dictated by working with a high-pressure molten alkali metal. The room has been outfitted with 100 amps of 208 V power to supply the heaters on the system. A central vacuum pumping station was also constructed to provide a vacuum capability of better than 10^{-6} Torr to the stripper system as well as other RIA-related test systems. Most of the requisite valves, instrumentation and fittings have been procured. Drawings for the pressure and collection reservoirs have been completed and are currently out for bid. A system isometric is shown in Fig. 4.

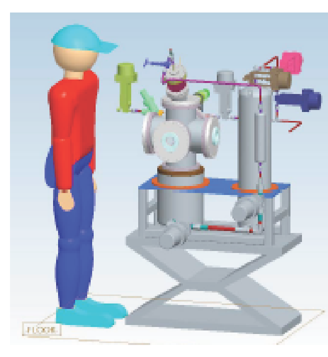

Figure 4. Isometric of Lithium Thin Film System.

Budget

The proposed FY2004 budget for this project was $1300K to cover 4 FTE of effort and $350K of M&S for hardware and diagnostics development. The project was funded at a total of $600K which has been allocated to 2 FTE of staff effort and one post-doctoral appointment plus $50K of M&S to initiate construction of the liquid lithium thin film test apparatus.